The Report Committee for Kaustubh Shrivastava
certifies that this is the approved version of the following report:

# Alternate-Slug Fracturing Using Foam

**APPROVED BY**
**SUPERVISING COMMITTEE:**

Supervisor: ___________________________________
Mukul M. Sharma

___________________________________
Kishore K. Mohanty

# Alternate-Slug Fracturing Using Foam

**by**

**Kaustubh Shrivastava, B. Tech.**

## Report

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

**Master of Science in Engineering**

**The University of Texas at Austin**
**August 2016**

## Dedication

To my parents for their love and blessings.

To my brother for his inspiration and support.

# Acknowledgements

Firstly, I would like to express my sincere gratitude to my advisor, Dr. Mukul Sharma, for his continuous support towards my research, for his patience, motivation, and immense knowledge. I could not have imagined having a better advisor and mentor for my graduate study. My sincere thanks also goes to Mr. Rod Russell, who has helped me all along, to build my experimental setup. Without his efforts and guidance, it would not have been possible to complete this work. Finally, I thank my friends, Robin Singh, Donna Vakharia, Juan Escobar, Himanshu Sharma, Shashvat Doorwar, Deepen Gala, Ashish Kumar, Prasanna Iyer, Dongkeun Lee, and Eva Vinegar for their support. I thank all my lab mates for making this journey memorable.

# Alternate-Slug Fracturing Using Foam

by

Kaustubh Shrivastava, M.S.E.

The University of Texas at Austin, 2016

Supervisor: Mukul M. Sharma

The success of a hydraulic fracturing job depends primarily on the proper distribution of proppant inside the fracture. Fracture length and conductivity are the two prime characteristics that determine the productivity of fractured wells (Liu & Sharma, 2005). Slick-water fracturing involves the use of large volumes of water for fracturing shales and mudstones (Palisch, et al., 2010). The low viscosity of water increases the settling velocity of proppant, resulting in an ineffective lateral placement of the proppant. It also affects the vertical coverage of the proppant across the pay zone(s), rendering the fracturing process inefficient (Gadde, et al., 2004).

To improve proppant placement, a new technique was proposed by Malhotra et al. (2014), that involves pumping slugs of high viscosity and low viscosity fluids alternately, with most of the proppant being carried by the low viscosity fluid. Alternate injection of

high viscosity and low viscosity slugs creates a mobility contrast between the fluids and leads to the formation of viscous fingers. The viscous fingers provide a pathway for proppant transport. The higher velocity of the viscous fingers compared to the injection velocity of the fluid leads to deeper placement of proppant. In addition, viscous sweeps, due to the high viscosity slugs, push any proppant bank formed near the wellbore deeper into the fracture, thus creating longer fractures (Malhotra, et al., 2014).

In this study, we conducted an experimental investigation to obtain a fundamental understanding of the viscous fingering phenomena when water and foam are used as the low and high viscosity fluids, over a wide range of viscosity ratios. We have derived a relationship between finger-tip velocity and viscosity ratio of the fluids. This relationship will help in designing Alternate-slug fracturing treatments for the foam-water system.

# TABLE OF CONTENTS

# LIST OF FIGURES

# Chapter 1: Introduction

## 1-1 Motivation

Recent developments in horizontal drilling and fracturing technology have allowed the vast hydrocarbon reserves bound in shale formations to be economically produced. The recent boom in hydrocarbon production in the United States is a direct result of this technological advancement.

Hydraulic fracturing is a technique in which fractures are induced in the formation in order to increase the available area for hydrocarbon production. This leads to an enormous increase in the formation contact area with the wellbore, resulting in the economic recovery of hydrocarbons even from low permeability formations.

Proppant placement plays a critical role in determining the success of hydraulic fracturing jobs. This report focuses on a new method, Alternate-Slug Fracturing, to improve the placement and distribution of proppant inside the fracture. In the past this has been achieved by using polymers and water as the high and low viscosity fluids respectively. The process can be made more efficient and environmentally friendly by using foam as one of the fracturing fluids in the method.

## 1-2 Alternate-Slug Fracturing Using Foam

In recent years, slick-water fracturing, a fracturing technique utilizing water for carrying proppant, has become the primary choice for hydraulic fracturing treatments (Palisch, et al., 2010). It is believed that slick-water fracturing is successful largely due to its low cost and its ability to create large fracture areas compared to other techniques (Ely, et al., 2014). However, the low viscosity of slick-water enhances proppant settling and results in a shorter propped fracture length and height. (Mack, et al., 2014).

Several techniques are available as alternatives to slick water fracturing. A promising method, proposed by Malhotra et al. (2014) is the Alternate-Slug Fracturing technique (AST). In this technique alternate slugs of high viscosity fluid (crosslinked gel) and low viscosity fluid (water) are injected in the fracture with most of the proppant being carried in the low viscosity fluid. The mobility contrast of the fluids leads to generation of viscous fingers (fingers of low viscosity proppant carrying fluid in high viscosity fluid) inside the fracture. These fingers travel at a faster velocity compared to the injection velocity and hence, help in placing proppant deeper into the fracture. In addition, any proppant bank formed gets pushed deeper into the fracture with the high viscosity slug. This deeper placement of proppant increases the fracture half length. Experiments conducted by Malhotra et al. (2014) also showed that the AST places proppant with a better vertical distribution compared to slick-water fracturing.

The advantages associated with AST have motivated us to pursue research to improve this technique. AST requires large amounts of water for its execution. This can have an adverse effect on the communities and the environment. The objective of our study is to reduce the water consumption by replacing high viscosity cross linked gel with foam. It will also lead to better control of leak-off, reduce gel and formation damage, improve vertical distribution of proppant, and reduce pumping cost (Malhotra, et al., 2014).

# Chapter 2: Literature Review

## 2-1 Viscous Fingering in Hydraulic Fracturing Treatments

Viscous fingering in porous media has been a phenomenon of considerable interest in the field of hydrology, filtration and proppant placement in hydraulic fractures (Liu, et al., 2007) (Malhotra, et al., 2014), and enhanced oil recovery (Peters & Cavalero, 1990) (Li, et al., 2006). The first scientific investigation of this phenomenon was done by Hill in 1952. He studied the displacement of sugar liquors by water from columns of granular bone charcoal (Hill, 1952) (Xu, 1997). Later, Chouke et al. (1959) and Saffman and Taylor (1958) performed a rigorous linear stability analysis for a flat interface. This instability mechanism for a flat interface has become known as the 'Saffman and Taylor instability'. It is recognized that this phenomenon is associated with the instability of the interface, which arises due to the difference in viscosity and density of the fluid, or due to the surface tension at the interface.

Previous research conducted to investigate viscous instabilities in the field of petroleum engineering has focused on production and stimulation operations. Fredrickson and Broaddus (1976) observed creation of viscous fingers of low viscosity acid if the viscosity of the pre-flush is increased to 100 cp. Naceur and Economides (1989) showed the occurrence of viscous fingering when multiple stages of pad fluid and acid are injected. Although the above studies show interest in the phenomena of viscous fingering in hydraulic fracturing, very few studies have been directed towards exploitation of the phenomenon in proppant placement.

Pugh et al. (1978) used a new fracturing technique by pumping alternate volumes of sand-laden viscous fluids and thin spacer fluids. They expected to create fractures with "pillars" of sand and void space to improve oil production. They observed significant reduction in treatment costs and substantial improvement over other techniques using this method.

Ely et al. (1993) developed the technique of "pipelining" which exploits high differential viscosity to selectively place high concentrations of proppant across the well's producing zones. This technique utilizes the viscous fingering phenomena to place proppant across thin pay intervals. In 2007, Liu et al. proposed the idea of reverse hybrid fracturing which used viscous fingering to place proppant deeper into the fracture. The primary motivation of this technique was to use a high viscosity fluid as the pad to avoid tip screenout by reducing leak-off rate at the tip. They observed that the technique leads to reduction in settling rates by an order of magnitude. In 2013, Malhotra et al. proposed the Alternate-Slug Fracturing technique which uses injection of multiple alternate slugs of high viscosity fluid and low viscosity fluid during fracturing to improve the proppant placement and reduce the gel damage. In addition to viscous fingering, increased drag force in the polymer slugs displaces any proppant bank that may form near the well. They showed that AST leads to longer propped-fracture length and better vertical placement of proppant in the fracture.

# Chapter 3: Methodology

## 3-1 Background and Theory

Alternate-Slug Fracturing is a recently developed fracturing technique that increases the conductivity of the proppant pack by providing highly conductive pathways for hydrocarbons in the fracture (Malhotra, et al., 2014) (Malhotra, 2013). In this method (Figure 3-1), slugs of low viscosity fluid along with proppant is injected into slugs of high viscosity fluid. This leads to generation of viscous fingers. As these viscous fingers do not sweep the entire area available in the fracture, they travel at a faster rate compared to the injection velocity. In addition, any proppant bank that is formed is pushed deeper into the fracture by the high viscosity slugs.

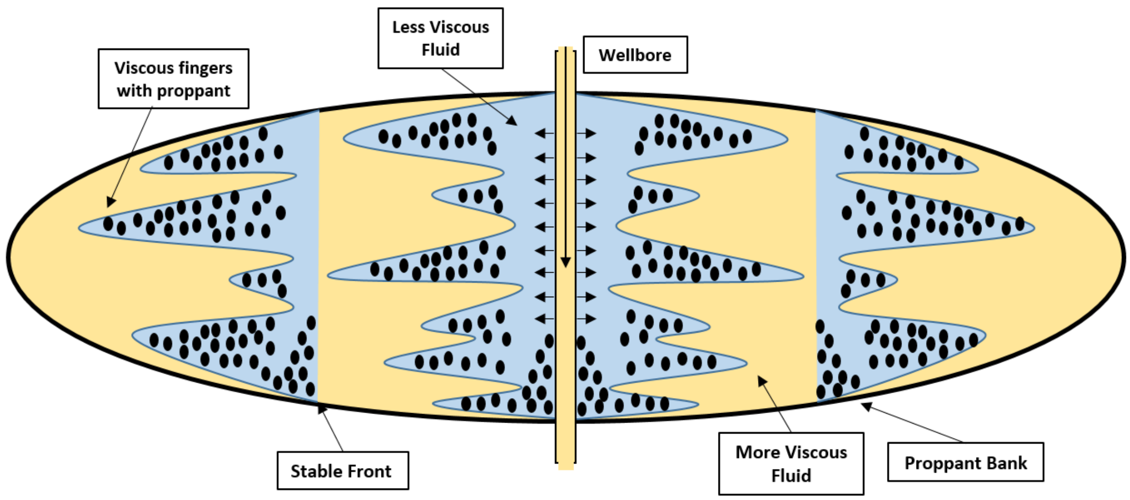



Figure 3-1: Alternate-Slug Fracturing in a fracture.

This method also provides better vertical placement of proppant, less gel damage in comparison to conventional fracturing treatments, reduced risk of tip screen-out, lower polymer costs, lower pumping power, smaller fracture widths and better fluid leak off control (Malhotra, et al., 2014). These associated advantages of the Alternate-Slug Fracturing technique (AST) make it an attractive fracturing treatment process.

In this study, we are trying to use foam in place of cross-linked gel as the more viscous fluid in AST. Foam is a Bingham pseudo-plastic fluid (Denkov, et al., 2009); hence, it exhibits excellent proppant transport characteristics (King, 1985). Foam also reduces the consumption of water by 40 to 50% in AST, which leads to rapid cleanup and further reduces gel damage (King, 1985).

Viscous fingering results from the formation of an unstable interface between two fluids. The instability is caused by the contrast in the mobility ratio. The mobility ratio is defined as,

$$M = \frac{\left(\frac{k_1}{\mu_1}\right)}{\left(\frac{k_2}{\mu_2}\right)} \tag{3.1}$$

where k is the permeability and μ represents the viscosity of the fluid. Subscripts 1 and 2 correspond to the displaced phase and displacing phase, respectively. It was shown by Saffman and Taylor (1958) that when two fluids of different viscosities experience an imposed pressure gradient, an unstable interface will be formed depending on the mobility ratio.

In the past, several experimental studies for understanding viscous fingering have been performed using Hele-Shaw cells (Chen, 1987) (Saffman, 1986) (Paterson, 1981). The Hele-Shaw cell comprises of two parallel plates with a thin gap between them and can be constructed to have rectilinear or radial flow.

### 3-2.1 Experimental Setup

Figure 3-2 shows the process flow diagram of the experimental setup. The experimental setup can be divided into three units. The first unit comprises the foam generation system. In this system, foam is produced by co-injecting a mixture of surfactant

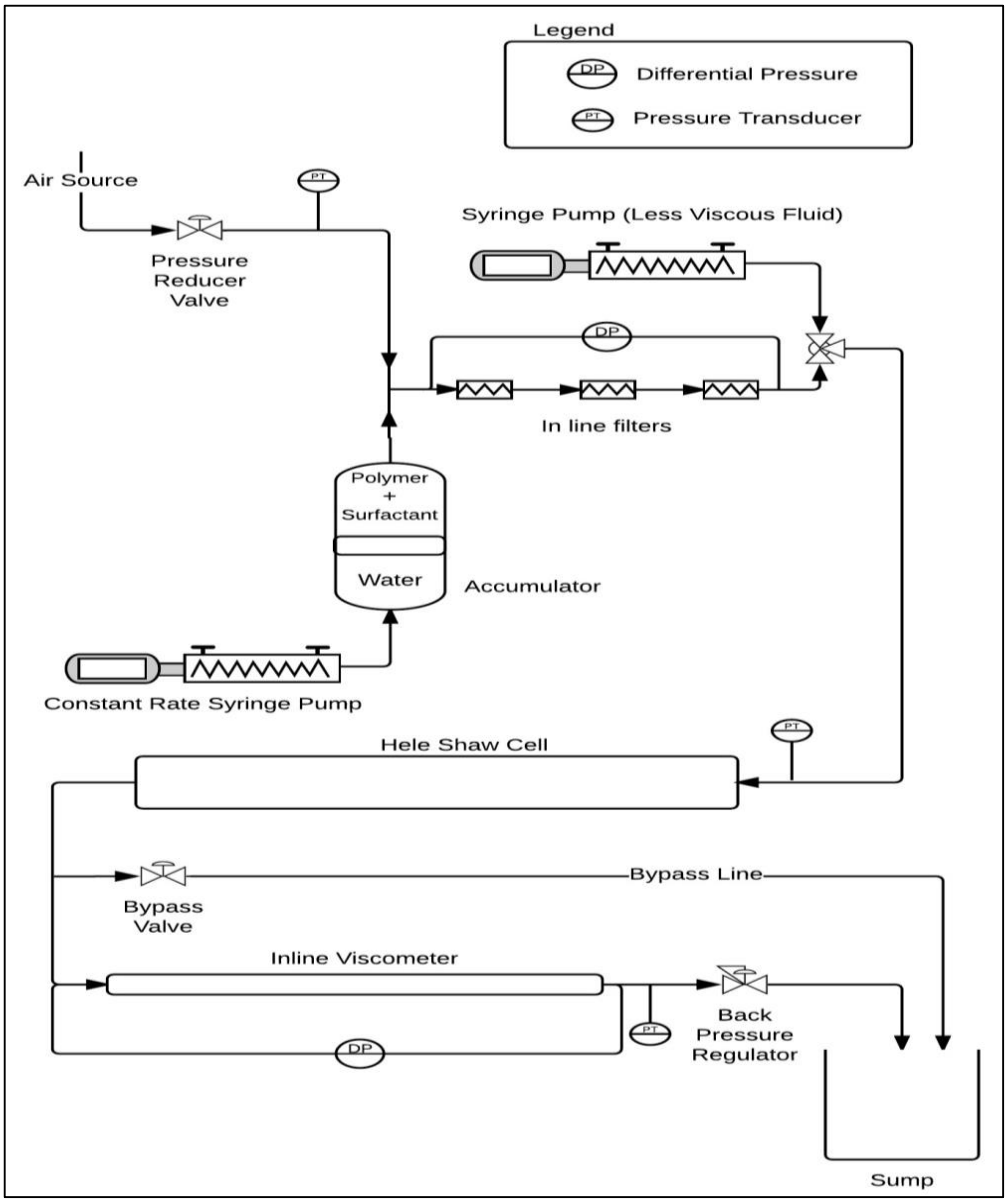
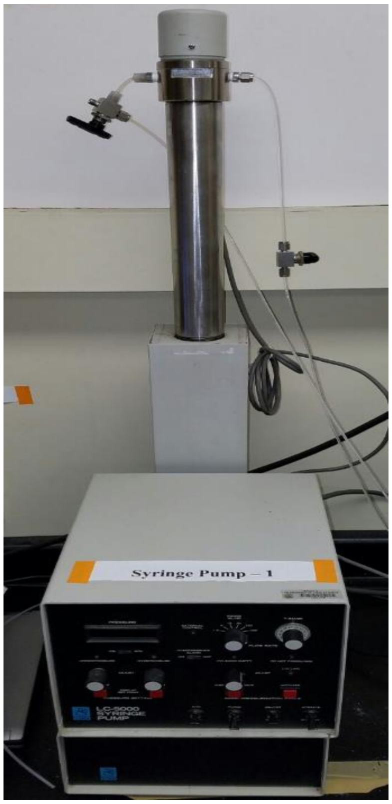



Figure 3-2: Process flow diagram of the experimental setup

and air through three inline-filters placed in series as shown in Figure 3-2. These filters provide the required shear for bubble generation.

Air is drawn from the main laboratory header at 105 psig into a pressure regulator. The pressure regulator is used to control the downstream pressure. The setup consists of a 500 ml ISCO syringe pump (Figure 3-3). It is used to pump water into the accumulator. The surfactant solution stored in the accumulator is pushed into the filters along with the air. The generated foam flows through the Hele-Shaw cell into the inline viscometer. A by-pass line is used to control the flow rate through the viscometer and measure viscosity at different shear rates.



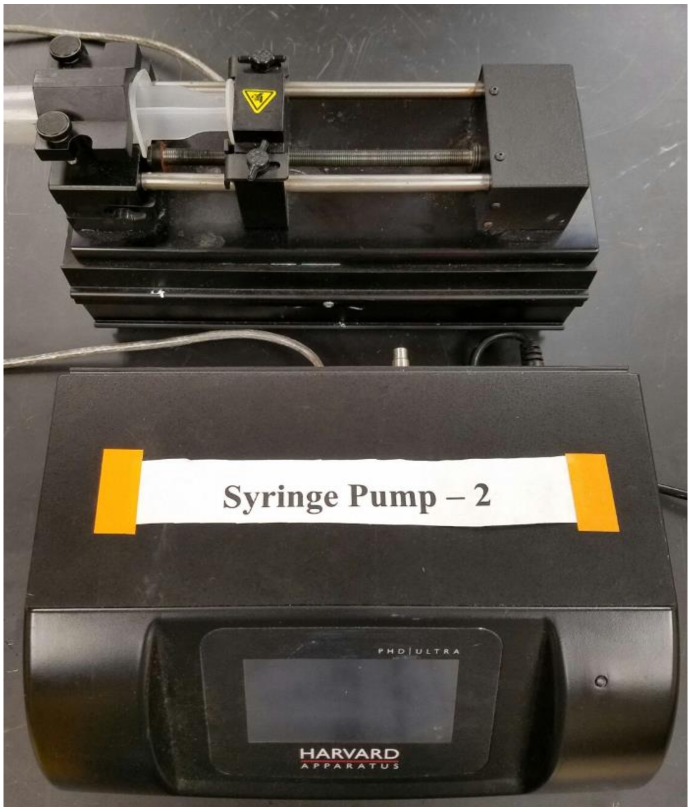




Figure 3-3:ISCO syringe pump(L) used for injection of surfactant solution. Harvard PHD syringe pump (R) used for injection of colored low viscosity fluid.

A second syringe pump (Figure 3-3), Harvard Apparatus PHD Ultra, is connected to the upstream end of the Hele-Shaw cell. It can be brought in-line using a three-way valve to pump the low viscosity fluid into the foam-filled cell. The low viscosity fluid is dyed blue using food coloring to obtain a visual contrast with the foam.

Figure 3-4 shows a sketch of the Hele-Shaw cell used in the experiments. The cell is made of Plexi-glass. The cell is 84 cm long and 5 cm wide. The walls of the cell are smooth and parallel to each other. The spacing between the two walls is 1mm but can be varied as needed.

A set of five Rosemount differential pressure transducers are used in the setup for pressure measurements. The transducers are used to measure the injection pressure of air, the pressure drop across the inline filters, the pressure drop across the Hele-Shaw cell, the differential pressure across the viscometer, and the pressure at the upstream of the back pressure valve. These pressure drops are monitored to verify that steady state flow conditions have been established in the system.

An inline pipe viscometer is used in the setup to determine the apparent viscosity of the foam flowing in the system. It consists of a stainless steel pipe with an internal diameter of 0.12 inches. The length of the pipe is 6 ft. The pressure drop is measured across the length of the pipe using Rosemount pressure transducers. A bypass line is available to vary the flow rate of foam through the viscometer. It helps to measure the viscosity of foam at different shear rates and capture the shear thinning nature of the foam.

A back-pressure regulator is installed at the outlet of the viscometer to conduct the experiments at an elevated pressure. The function of the back-pressure regulator is to minimize the change in pressure and, therefore, the foam quality while it flows through the apparatus.

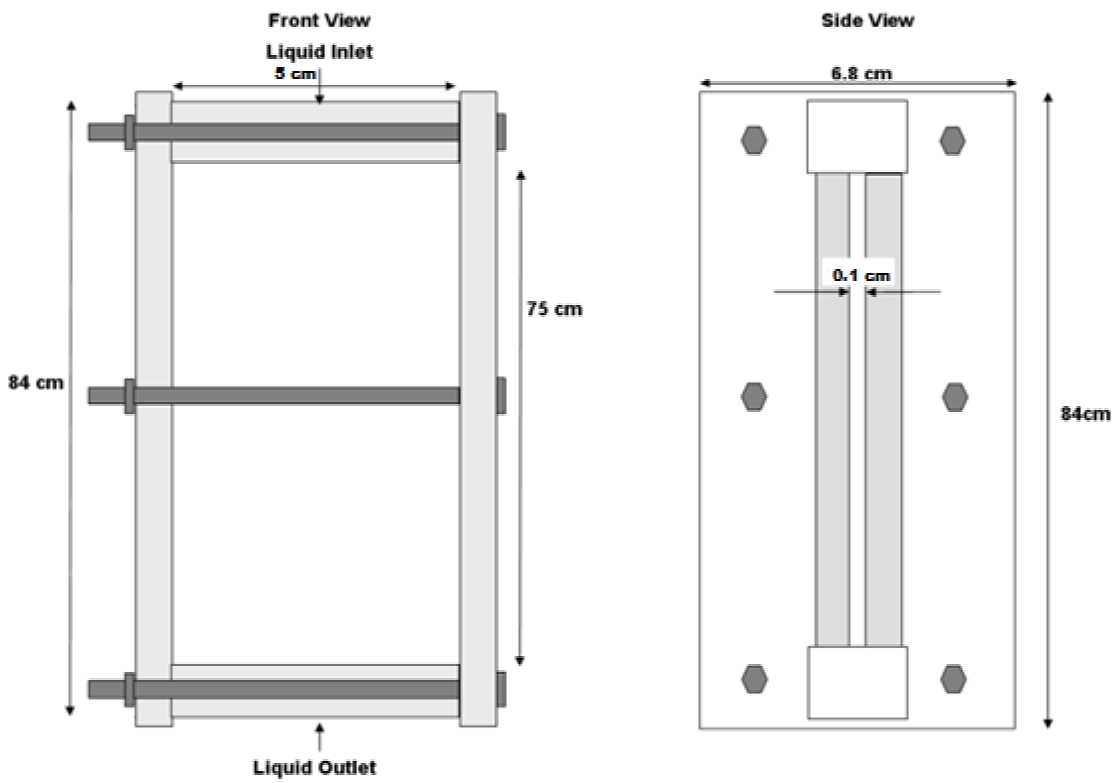



Figure 3-4: Hele-Shaw cell used in the experiment (Malhotra et al. 2013)

## 3-2.2 Solution Preparation

For the generation of foam, a base surfactant solution is used. The solution is prepared from a mixture of Sodium Dodecyl Sulfate (SDS), de-ionized water, and

Flopaam™ 3630S polymer. Sodium dodecyl sulfate powder with purity greater than 99% was obtained from Fisher Scientific. The concentration of SDS is maintained at 0.5 wt % and the polymer concentration is maintained at 1000 ppm.

For the preparation of the solution, the surfactant is dissolved in DI water using a magnetic stirrer. After achieving complete dissolution of the surfactant in DI water, polymer is added to the surfactant solution, which is continuously stirred to avoid agglomeration of the polymer. The mixing is performed in an inert environment to avoid oxidation of the polymer. The inert environment is maintained using nitrogen gas. The solution is then stirred for 18-24 hours at 500 rpm for complete hydration of the polymer.

The injected low viscosity fluid is prepared by mixing 10 drops of blue food coloring per liter of tap water. This solution is stirred until a uniform color is obtained.

## 3-3 Experimental Procedure

The experiment can be divided into three steps. The first step is the generation of a constant quality of foam. Air and surfactant solution are co-injected through the inline filters. The filters act as a porous medium and provide the required shear for the foam generation. The Hele-Shaw cell is allowed to be filled completely with the foam. The foam is then flowed through the system until steady state is achieved. The attainment of the steady-state is confirmed by observing stabilization of the pressure drop across all the pressure transducers. The injection rate of the surfactant solution can be controlled to achieve the desired foam quality.

In the next step of the experiment, rheometric characterization of the foam is conducted. The flow rate of the foam through the inline viscometer is varied by controlling the valve opening on the bypass line. The pressure drop is measured for each flow rate of the foam and a stress-strain curve is plotted to obtain its rheology.

The foam quality is measured by filling a vial of known volume with the produced foam and measuring its weight. The following formula is used to compute the foam quality:

$$q = 1 - \frac{w}{v\,\rho} \tag{3.2}$$

where q is the foam quality, w is the measured weight of the foam, v is the volume of the vial, ρ is the density of the surfactant solution.

After achieving steady state, flow of the foam through the Hele-Shaw cell is stopped and the water syringe pump is brought in line with the Hele-Shaw cell using a three-way valve. The syringe pump is used for injecting colored water into the foam filled cell at different injection rates.

The injection leads to generation of the viscous fingers as low viscosity fluid (water) displaces high viscosity fluid (foam). This phenomenon is captured using a high-resolution video camera. The camera is placed over the top of the cell using a tripod and is moved along the length of the cell during the experiment to capture the progress of the created fingers. A meter scale is placed alongside the cell to use as a reference scale. The recorded video is then used to track the position of the viscous finger-tip and to measure the finger-tip velocity.

A video analysis software, “Tracker 4.0”, is used to get accurate measurements of the finger-tip velocity from the recorded video. Figure 3-5 is a snapshot from the software application showing the finger-tip being tracked at fixed time steps. The x-position of finger-tip is tracked as a function of time.

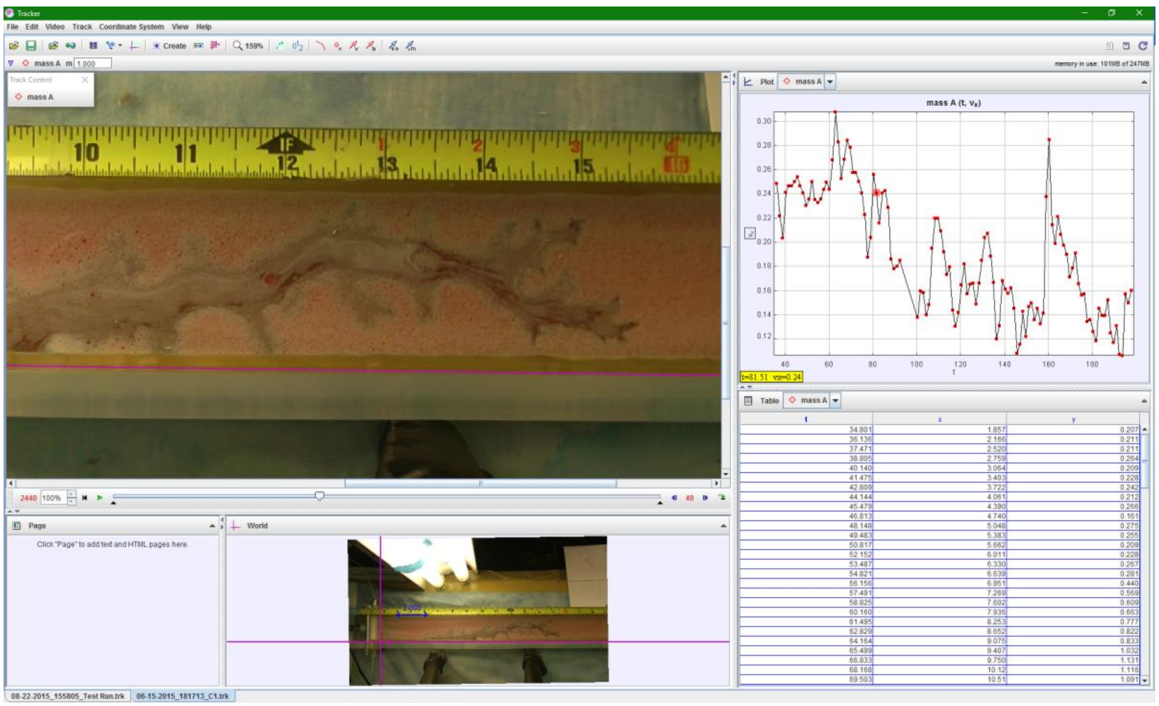



Figure 3-5: Snapshot of Tracker 4.0 while determining the velocity of a viscous finger.

# Chapter 4: Results and Discussion

## 4.1 Foam rheology

Figure 4-1 shows the rheology data for three different quality of foam. It can be seen that foam has a shear thinning nature. At low shear rates, it has a very high viscosity, which is the result of the plastic nature of foam. Hence, foam exhibits excellent proppant carrying properties **(King, 1985)**, especially at low shear rates.

It is also observed that the viscosity of foam increases as quality of foam increases. Hence, higher quality foam should provide better proppant transport.

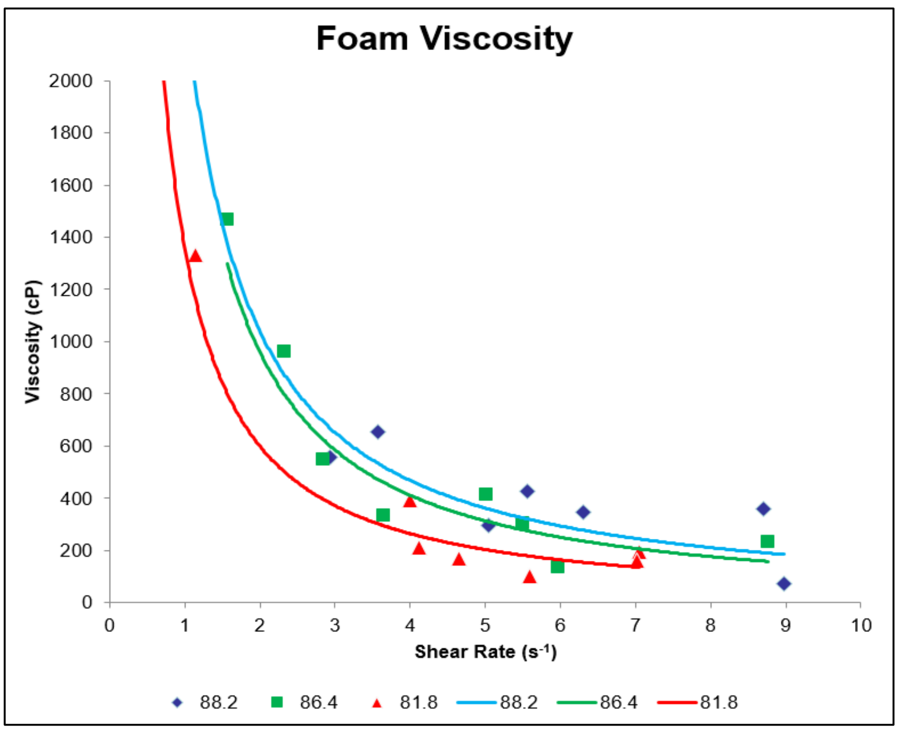



Figure 4-1: Rheology of foam for different foam quality.

## 4.2 Bubble size

Figure 4-2 shows a microscopic image of the Hele-Shaw cell filled with foam. The average bubble diameter of the foam was determined by counting the number of bubbles in the image. The diameter was found to be 125 microns (Figure 4-2). The quality of the foam is 87.4 percent. As there are multiple layers of foam bubbles in the Hele-Shaw cell, the above method is not suitable for studying the effect of foam diameter on viscous fingering **(Khan, et al., 1988)**, and here, it is only used to give an approximate bubble diameter.

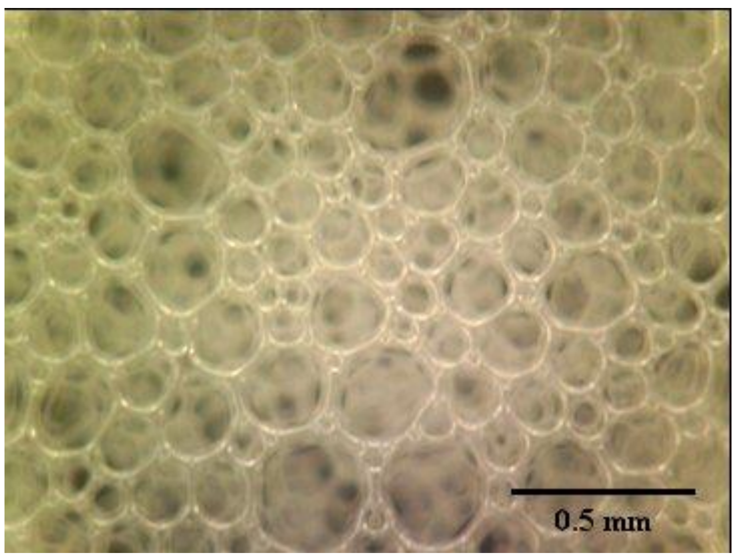



Figure 4-2: Microscopic image of bubbles in Hele-Shaw cell.

## 4.3 Comparison with polymeric fluids

Compared to the gel-water fluid system, in the foam-water system it is observed that the less viscous fluid does not completely displaces the more viscous fluid across the width. This can lead to formation of thin layers of foam between the viscous fingers of water, even very close to the wellbore (injection port). Entrapment of proppant particles in these high viscosity layers of foam can occur and provide better vertical distribution of the proppant. Further, it can reduce the tendency of proppant bank formation as these layers are present very close to the injection point.

In the foam-water system, a more pronounced dominant finger is observed compared to the gel-water viscous fingering experiments conducted by Malhotra et al. (2013). The number of fingers formed during the foam-water experiment is also less. The shape of the finger is retained for a longer duration in the foam-water system. This reduces the tendency of proppant to form a bank near the wellbore, hence, it can lead to a deeper placement of proppant.

## 4.4 Particle settling experiment in foam

The experimental setup is also used to investigate the settling of particles in the generated foam. A spherical glass bead with a diameter of 2 mm is used for the experiment. The glass bead is colored using a permanent marker to make it distinctly visible. The Hele-Shaw cell used for the experiment is 16 inches long, 2.2 inches wide and has a spacing of 3.6 mm between the plates.

The glass bead is injected along with the foam from the injection port of the Hele-Shaw cell. The injection flow rate of the foam is maintained at 0.95 cc/sec, the highest injection rate possible in the experimental setup. The experiment is performed at atmospheric pressure. The trajectory of the particle is tracked using Tracker 4.0 (Figure 4-3).

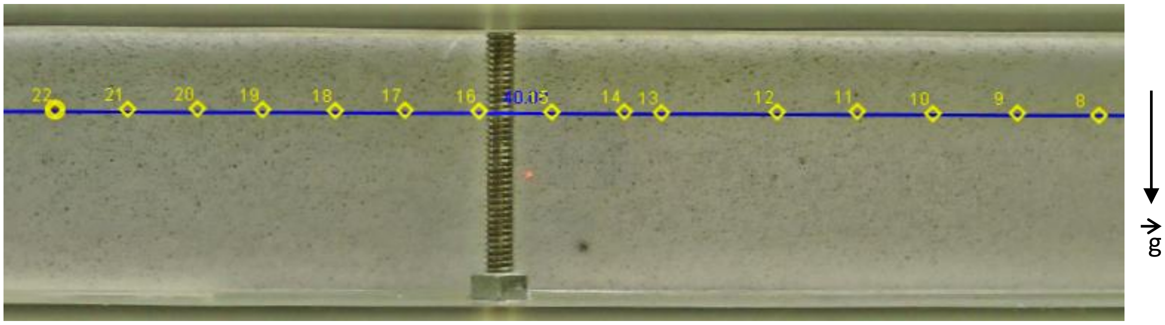



Figure 4-3: Trajectory of a 2 mm spherical particle in horizontal Hele-Shaw cell. Diamonds indicate the location of the glass bead for different frames. The quality of foam is 90.1 percent. The concentration of the polymer and surfactant is 1000 ppm and 0.5 wt percent respectively.

No settling of the glass-bead is observed during the experiment. This is due to the Bingham-plastic nature of the foam at low shear rates. It indicates the exceptional proppant carrying capacity of foam.

## 4.4 Effect of polymer addition

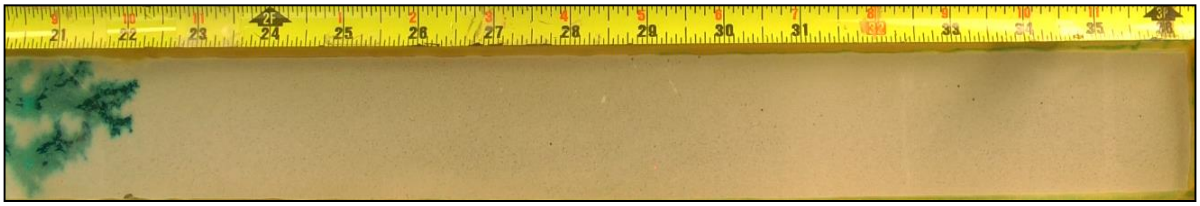
The foam used in the experiment is prepared by adding a polymer to the base surfactant fluid. The viscous fingering phenomenon is not observed in the absence of polymer. Figure 4-4 shows a case of water injection into a cell filled with foam formed without polymer in its base fluid. The addition of polymer increases the viscosity of the foam. In addition, it also improves its stability by reducing the drainage rate **(Harris, 1996)**. In the absence of the polymer, the resistance of flow in the lamellae of the foam is reduced and it acts as a channel for the injected fluid. The absorption of water in the foam through the lamellae reduces the quality of the foam and decreases the contrast between the viscosities of the foam and the injected-water. This prevents viscous fingers from forming. Viscous fingers were not observed when the foam was unstable and its viscosity degraded as it mixed with the displacing fluid (water).

Figure 4-4: Injection of water into foam (without polymer in the base fluid). The viscous fingering phenomenon is not observed. The pink color depicts clear fluid(water) and white color is due to foam bubbles.

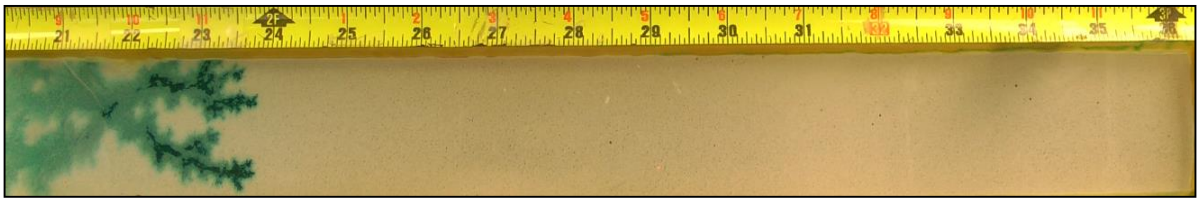
## 4.5 Results of viscous fingering experiment in the flow cell

Figure 4-5 shows snapshots of the captured video at intervals of 10s from the start of the video. We can clearly observe the phenomena of tip splitting and shielding. The finger splits into two or more fingers, and after splitting, only the dominant finger continues to grow. It shields/retards the growth of other fingers. This mechanism is referred to as uneven tip splitting. The dominant finger has a tendency to move towards the center of the cell indicating that the fingers can perceive the cell walls. This is in accordance with the observations made by Linder et al. (2000) and indicates the absence of the yield stress regime for the foam. This is because of the wall slip between the foam and the plexiglass cell walls.

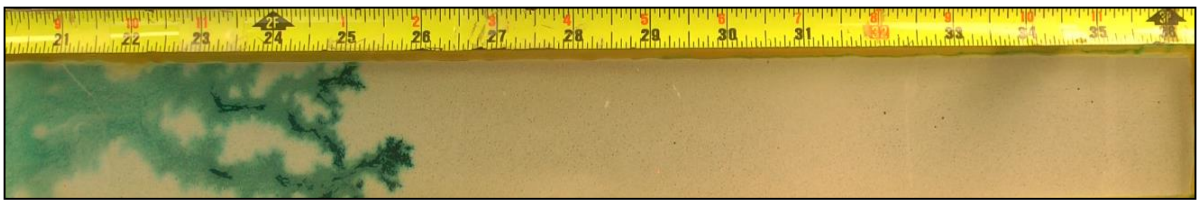
Figure 4-6 shows a plot between the tracked finger-tip x-position and time. The slope of the graph indicates a constant finger-tip velocity during the experiment. The constant velocity observed amidst a visibly random phenomenon of viscous fingering reinforces our confidence of using this parameter for the design of Alternate-Slug Fracturing treatments.



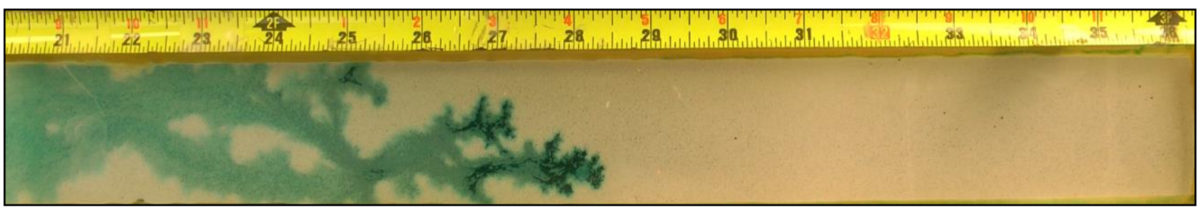

**T = 0 s**



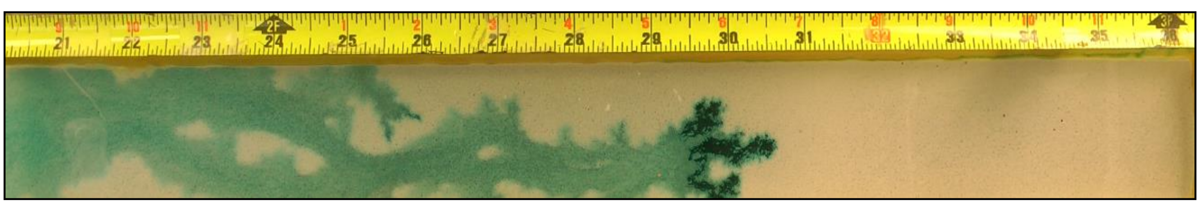

**T = 10 s**



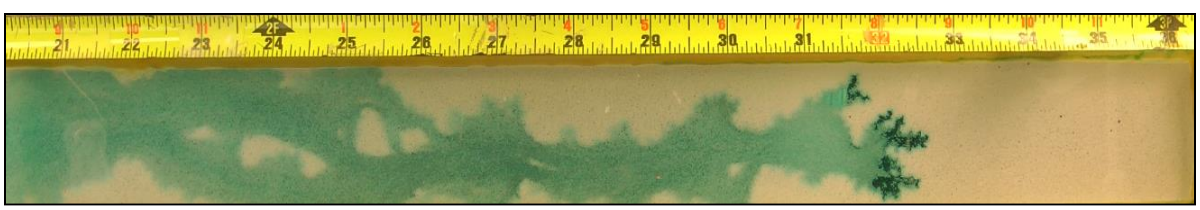

**T = 20 s**




**T = 30 s**




**T = 40 s**




**T = 50 s**

Figure 4-5: Snapshots of finger growth during the injection of water in foam filled Hele-Shaw cell. The concentration of polymer and surfactant is 1000 ppm and 0.5 wt percent respectively. Quality of the foam is 89.7 percent. The superficial velocity of low viscosity fluid is 10 cm/min.

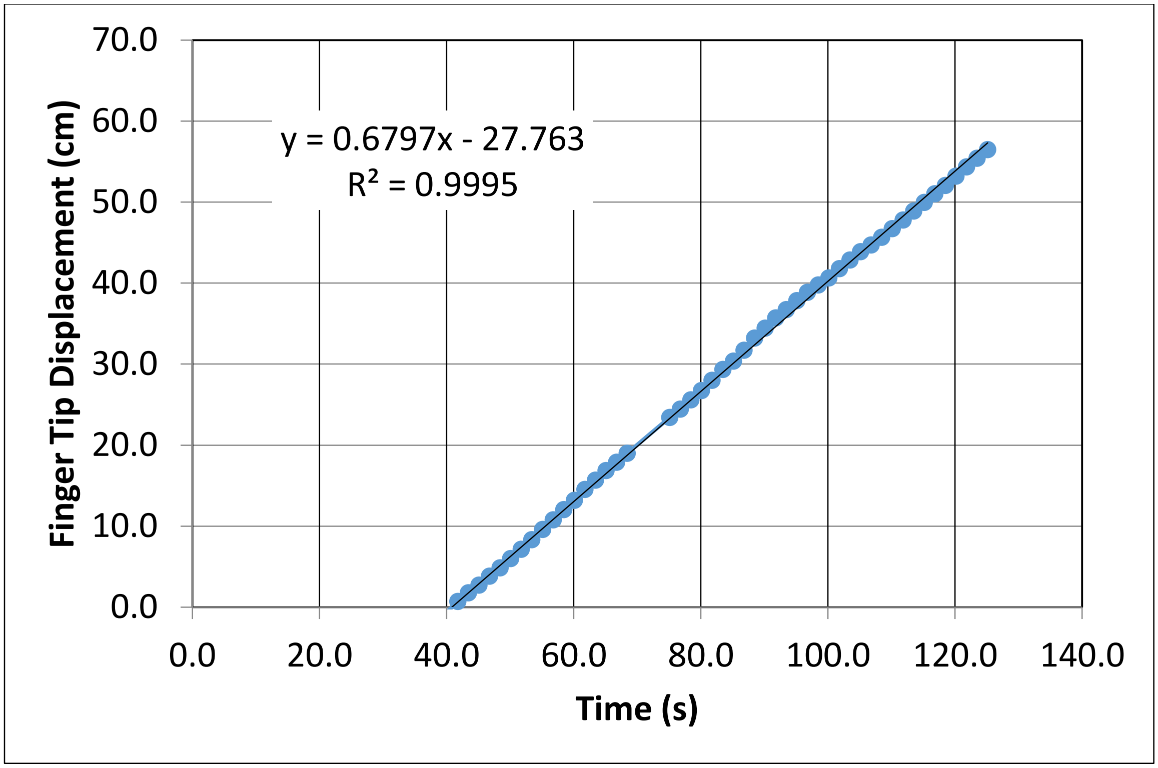



Figure 4-6: Finger-tip displacement as a function of time for one of the experiments. Quality of the foam is 89.7 percent. The superficial velocity of low viscosity fluid is 10 cm/min.

Several experiments were conducted for different injection rate and foam quality to observe the variation of the relative finger-tip velocity vs the viscosity ratio. Relative finger-tip velocity is defined as the ratio of finger-tip velocity to the injection velocity (injection rate divided by the cross sectional area of the cell). Viscosity ratio is defined as the ratio of the foam to the viscosity of the injected fluid. Figure 4-7 shows the comprehensive results of the experiments. It can be observed that the nature of the curve observed for the foam water system is very similar to the one observed by Malhotra et al. (2014) for the cross-linked gel water system.

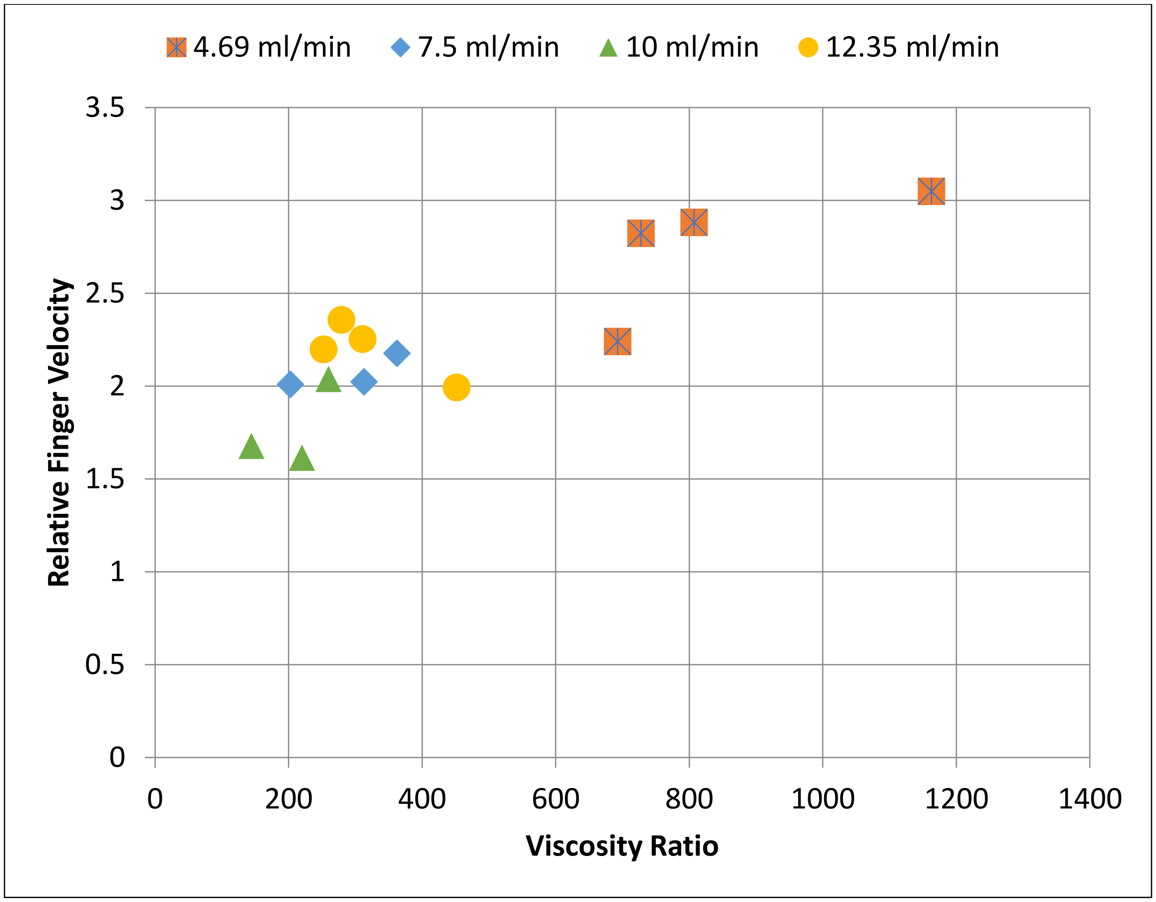



Figure 4-7: Relationship between relative finger velocity and viscosity ratio for different injection rate. The viscosity of the foam is calculated at the shear rate experienced in the Hele-Shaw cell during the experiment.

The similar result is obtained because of the shear-thinning nature of both the foam and the cross-linked gel and the suppression of the Bingham-plastic characteristic of foam. This is due to the presence of wall-slippage between the foam and the plexi-glass surface.

# Chapter 5: Conclusions and Future Work

## 5-1 Conclusions

This report investigates the feasibility of using foam as the high viscosity fluid in the Alternate-Slug fracturing technique (AST). Based on the experiments conducted the following conclusions can be obtained.

1. We have demonstrated the formation of viscous fingers of water in foam in a Hele-Shaw cell.
2. The viscosity of foam increases as the quality of foam increases.
3. In the case of foam-water viscous fingering experiments, shielding is more pronounced and it leads to growth of only a few dominant fingers compared to several competing fingers in the case of gel-water viscous fingering experiments.
4. Partial displacement of the high viscosity fluid is observed in the foam-water case, whereas, a complete displacement is observed in the gel-water case. This may lead to an improved vertical distribution of proppant for foam-water based ASTs.
5. The velocity of finger propagation increases as the viscosity ratio between the two fluid phases increases. The experimental results show that for a unique viscosity ratio, the velocity of finger-tip remains constant throughout the experiment.

6. An experimental correlation between the finger-tip velocity and the viscosity ratio has been obtained.

This experimental study shows that it is possible to use foam as the high viscosity fracturing fluid in the alternate slug treatments in the field. The correlation developed in this study will be useful in designing ASTs using foam. The use of foam in AST will provide several advantages over current methods of using slick-water for hydraulic fracturing. It will reduce water consumption, reduce gel damage, and improve proppant transport resulting in better proppant placement at lower fluid and pumping costs.

## 5-2 Future Work

In the future, we plan to extend this study to conduct experiments to investigate the transport of proppant in AST using the foam-water system. It will help us demonstrate the effectiveness of using foam in AST.

High conductivity channels are formed above the proppant bank inside a fracture (Cipolla, et al., 2009). These channels are formed due to the uneven distribution of proppant. It has been shown in the literature that these channels can significantly increase the fracture permeability and production from a hydraulic fracture.

We plan to investigate proppant distribution using AST in radial Hele-Shaw cells. This will help us to demonstrate the potential of AST to create multiple high conductivity channels in vertical fractures with horizontal wellbores.

# References


Ben-Naceur, Kamel., and Economides, Michael J. 1989. Design and Evaluation of Acid Fracturing Treatments. Presented at the Low Permeability Reservoirs Symposium, Denver, Colorado, 6-8 March. SPE-18978-MS. http://dx.doi.org/10.2118/18978-MS.

Chen, J-D. 1987. Radial viscous fingering patterns in Hele-Shaw cells. *Experiments in fluids* **5** (6): 363-371. http://dx.doi.org/http://dx.doi.org/10.1016/0009-2509(52)87017-4.

Chouke R.L., van Meurs, P., and van der Poel, C. 1959. The Instability of Slow, Immiscible, Viscous Liquid-Liquid Displacements in Permeable Media. *Petroleum Transactions AIME* **216** :188-194. SPE-1141-G.

Cipolla, Craig L., Lolon, Elyezer., Mayerhofer Michael J. et al. 2009. The Effect of Proppant Distribution and Un-Propped Fracture Conductivity on Well Performance in Unconventional Gas Reservoirs. Presented at the SPE Hydraulic Fracturing Technology Conference, The Woodlands, Texas, 19-21 January. SPE-119368. http://dx.doi.org/10.2118/119368-MS.

Denkov, Nikolai D., Tcholakova, Slavka., and Golemanov, Konstantin. 2009. The role of surfactant type and bubble surface mobility in foam rheology. *Soft Matter* **5** (18): 3389-3408. http://dx.doi.org/10.1039/B903586A.

Ely, J.W., Hargrove, J.S., Wolters, B.C. et al. 1993. "Pipelining": Viscous Fingering Prop Fracture Technique Finds Wide Success in Permian and Delaware Basins. Presented at the SPE Annual Technical Conference and Exhibition, Houston, Texas, 3-6 October. SPE-26528-MS. http://dx.doi.org/10.2118/26528-MS.

John W. Ely., Fowler, Steven L., Tiner, Robert L. 2014. "Slick Water Fracturing and Small Proppant" The future of stimulation or a slippery slope? Presented at the SPE Annual Technical Conference and Exhibition, Amsterdam, The Netherlands, 27-29 October. SPE-170784-MS. http://dx.doi.org/10.2118/170784-MS.

Broaddus G.C., Fredrickson, S.E. 1976. Selective Placement of Fluids in a Fracture by Controlling Density and Viscosity. *Journal of Petroleum Technology* **28** (5): 597-602. SPE-5629-PA. http://dx.doi.org/10.2118/5629-PA.

Gadde, Phani B., Liu, Yajun., Norman, Jay. et al. 2004. Modeling Proppant Settling in Water-Fracs. Presented at the SPE Annual Technical Conference and Exhibition, Houston, Texas, 26-29 September. SPE-89875-MS. http://dx.doi.org/10.2118/89875-MS.

Harris, Phillip C. 1996. Rheology of Crosslinked Foams. *SPE Production & Facilities* **11** (2): 113-116. SPE-28512-PA. http://dx.doi.org/10.2118/28512-PA.

Hill, S. 1952. Channeling in packed columns. *Chemical Engineering Science* **1** (6): 247-253. http://dx.doi.org/10.1016/0009-2509(52)87017-4.

Homsy, George M. 1987. Viscous fingering in porous media. *Annual review of fluid mechanics* **19** (1): 271-311. http://dx.doi.org/10.1146/annurev.fl.19.010187.001415.

Khan, Saad A., Schnepper, Carol A., and Armstrong, Robert C. 1988. Foam Rheology: III. Measurement of Shear Flow Properties. *Journal of Rheology* **32** (1): 69-92. http://dx.doi.org/10.1122/1.549964.

King, George K. 1985. Foam and Nitrified Fluid Treatments-Stimulation Techniques and More. Society of Petroleum Engineers. SPE-14477-MS.

Li, H., Maini, B., and Azaiez, J. 2006. Experimental and Numerical Analysis of the Viscous Fingering Instability of Shear-Thinning Fluids. *The Canadian Journal of Chemical Engineering* **84** (1): 56-62. http://dx.doi.org/10.1002/cjce.5450840109.

Lindner, Anke., Coussot, Philippe., and Bonn, Daniel. 2000. Viscous fingering in a yield stress fluid. *Physical Review Letters* **85** (2): 314-317. http://dx.doi.org/10.1103/PhysRevLett.85.314.

Liu, Yajun., Gadde, Phani Bhushan., and Sharma, Mukul Mani. 2007. Proppant Placement Using Reverse-Hybrid Fracs. *SPE Production & Operations* **22** (3): 348-356. SPE-99580-PA. http://dx.doi.org/10.2118/99580-PA.

Liu, Y., Sharma, Mukul M. 2005. Effect of Fracture Width and Fluid Rheology on Proppant Settling and Retardation: An Experimental Study. Presented at the SPE Annual Technical Conference and Exhibition, Dallas, Texas, 9-12 October. SPE-96208-MS. http://dx.doi.org/10.2118/96208-MS.

Mack, Mark., Sun, Juan., and Khadilkar, Chandra. 2014. Quantifying Proppant Transport in Thin Fluids: Theory and Experiments. Presented at the SPE Hydraulic Fracturing Technology Conference, The Woodlands, Texas, 4-6 February. SPE-168637-MS. http://dx.doi.org/10.2118/168637-MS.

Malhotra, S. 2013. Role of Fluid Elasticity and Viscous Instabilities in Proppant Transport in Hydraulic Fractures. PhD Thesis, The University of Texas at Austin, Austin, Texas.

Malhotra, Sahil., Lehman, Eric R., and Sharma, Mukul M. 2014. Proppant Placement Using Alternate-Slug Fracturing. *SPE Journal* **19** (5): 974-985. SPE-163851-PA. http://dx.doi.org/10.2118/163851-PA.

Palisch, Terrence T., Vincent, Michael., and Handren, Patrick J. 2010. Slickwater Fracturing: Food for Thought. *SPE Production & Operations* **25** (3): 327-344. SPE-115766-PA. http://dx.doi.org/10.2118/115766-PA.

Paterson, Lincoln. 1981. Radial fingering in a Hele Shaw cell. *Journal of Fluid Mechanics* **113** (1): 513-529. http://dx.doi.org/10.1017/S0022112081003613

Peters, E. J., Cavalero, S.R. 1990. The Fractal Nature of Viscous Fingering in Porous Media. Presented at the SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, 23-26 September. SPE-20491-MS. http://dx.doi.org/10.2118/20491-MS.

Pugh Jr., T. D., McDaniel, B.W., and Seglem, R.L. 1978. A New Fracturing Technique for Dean Sand. *Journal of Petroleum Technology* **30** (2): 167-172. SPE-6378-PA. http://dx.doi.org/10.2118/6378-PA.

Saffman, P. G. 1986. Viscous fingering in Hele-Shaw cells. *Journal of Fluid Mechanics* (173): 73-94. http://dx.doi.org/10.1017/S0022112086001088.

Saffman, Philip Geoffrey., and Taylor, Geoffrey. 1958. The penetration of a fluid into a porous medium or Hele-Shaw cell containing a more viscous liquid. *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* **245** (No. 1242): 312-329.

Jian-Jun Xu. 1998. *Interfacial Wave Theory of Pattern Formation.* Heidelberg, Germany. Springer-Verlag.